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NASA
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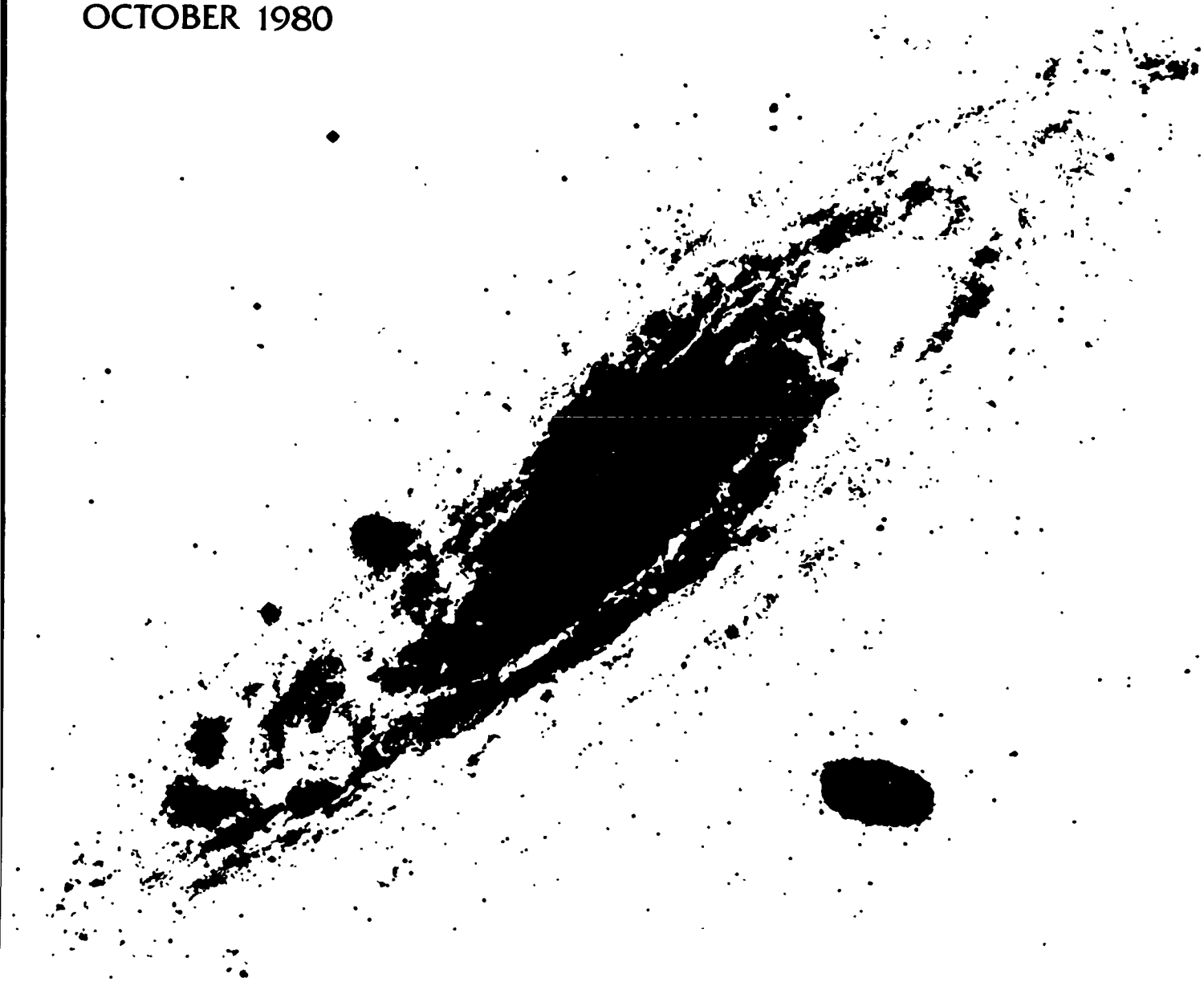
ASTROPHYSICS PROGRAM

PROJECT CONCEPTS:

Relativistic Gravitation Experiments

OCTOBER 1980



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FOREWORD

This document is one in a series describing projects of current interest in NASA astrophysics planning. Some of these projects were originally suggested by the Space Science Board of the National Academy of Sciences and the Outlook for Space Study Group. Others have been suggested by various internal working groups. Still others have been suggested by individual scientists or scientific groups both within NASA and in the broad astrophysics community. The descriptions presented in these volumes are based on technical studies or preliminary assessments done by NASA's Ames Research Center, Goddard Space Flight Center, Marshall Space Flight Center, and the Jet Propulsion Laboratory. Since the projects are at various stages in the planning process, the level of detail presented gives our current best estimate of the scientific objectives and technical characteristics. Where variations such as alternative strawman payload combinations have been studied, these are presented, and their effects on the overall project are discussed. Specific spacecraft, and other systems or subsystems, are identified or implied in many cases to illustrate that a concept for conducting the project exists. Such identification does not reflect a commitment on the part of NASA to utilize such hardware should the project be implemented. Similarly, in the actual implementation of any particular project, details will inevitably change. Our objective in assembling these documents has been to produce a set of concise project descriptions in a uniform format. They are intended to serve as a basis for discussion within the astrophysics community and to help determine how individual missions can best be accommodated within NASA's overall astrophysics program.

This document was prepared by R. Decker, P. B. Eby and C. A. Lundquist of the Marshall Space Flight Center and J. B. Anderson of the Jet Propulsion Laboratory.

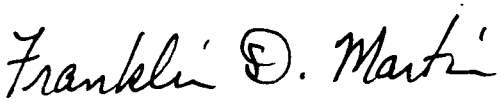

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Table of Contents

Foreword 2

Overview 5

Introduction 6

Synopsis of Experiments 7

Orbital Cryogenic Eötvös Experiment 11

Hydrogen Maser Redshift Experiment 15

Beta-Decay Clock Experiment 18

Venus Orbiting Imaging Radar (VOIR) 21

Mercury Orbiter 23

Solar Probe 25

Solar Coronal Sounder 26

RELATIVISTIC GRAVITATIONAL EXPERIMENTS

OVERVIEW

This brochure describes several possible gravitational physics experiments and missions. The experiments and missions discussed in the following sections cover a variety of specific science objectives including different tests of the Equivalence Principle as well as measurements of relativistic gravity phenomena in the solar system. Table 1 gives a summary of mission characteristics.

None of these missions has been formally studied, and the descriptions present concepts rather than detailed systems design. No commitment has been made to fly the missions and experiments described.

TABLE 1. Experiment Characteristics

Proposed Experiment	Life (yr)	Mass (kg)	Orbit	Considerations
Orbital Cryogenic Eövtös Experiment	0.5	900	400 to 600 km Earth orbit	Modest cost: might be Explorer candidate
Hydrogen Maser Redshift Experiment	0.3	200	Highly eccentric nearly geosynchronous orbit	Modest cost: might be Explorer candidate
Beta-Decay Clock Experiment	several yrs	several kg	Highly eccentric solar orbit	Experiment addition to interplanetary mission
Venus Orbiter Imaging Radar	2	(a)	Near circular Venus orbit	Modification costs for tracking system
Mercury Orbiter	1	(a)	Near circular Mercury orbit	Modification costs for tracking system
Solar Probe	3.5	(a)	Earth to Sun with Jupiter assist	Modification costs for tracking system
Solar Coronal Sounder	2.5	(a)	Superior conjunction at heliocentric distance of 1 AU	Modification costs for tracking system

(a) Mass impact to mission is minimal.

INTRODUCTION

Gravitation is one of the four fundamental forces in nature together with electromagnetic forces and the weak and strong interactions of particle physics. Gravitation is a dominating force in the universe. It governs the large-scale evolution of the universe and plays a major role in more local and often violent events such as star formation and collapse into compact objects and, ultimately, even black holes. On a laboratory scale, gravitation is still a vital effect which must be considered. More than the other fundamental forces, gravitation is the force that man perceives with his own senses.

As a scientific discipline, the study of gravitation now stands rooted equally in at least three important strong camps. First, the physics community must deal with gravitation as one of its foundational concepts. There, renewed attempts to formulate a theory unifying gravitation and the other fundamental forces show promising progress, thus stimulating a burst of activity in the physics camp. Second, the astronomy community currently observes many objects in the universe whose comprehension demands a deep understanding of gravitation. The catalog of such objects grows rapidly, accelerated by results from observatories in space. Hence, the astronomers are driven to hot pursuit of gravitational topics. Third, the space research practitioners have attained a level of sophistication and precision that allows performance of significant controlled experiments in gravitational science. The decades are past when theories of gravitation, such as Einstein's, depended on three or so classical experimental tests. Of course, the three camps, physics, astronomy, and space research, are not isolated from each other. Each mutually supports and depends on the others. Together, they constitute a vigorous constituency for studies of gravitation.

SYNOPSIS OF EXPERIMENTS

Objectives

This booklet addresses a collection of future opportunities for gravitational experiments in space. They should be viewed in the context of the previous paragraph. On one hand, the experiments provide evidence to support, refute, or guide the theories evolved by the physics community. In most cases a space experiment is the only known way to probe a particular aspect of a theory. On the other hand, the space experiments explore phenomena whose existence may be inferred from astronomical observations. Results of controlled experiments in space are essential to assure a proper interpretation of astronomical observations. An experimentally verified understanding of gravitational phenomena allows the confident use of astronomical observations to deduce facts about the objects observed.

The particular experiments discussed in the subsequent sections of this booklet should also be considered in relation to other investigations either already performed or treated in other booklets of this series. Table 2 shows these relationships. The Relativity Gyroscope Experiment was judged to be of such maturity that it warrants an individual booklet. Nevertheless, in spirit it is like the topics discussed here which at present have had less development effort. The search for gravitational radiation has unique features that likewise warrant a separate booklet.

Important links between the gravitational radiation booklet and this booklet deserve mention. One concept for a radiation search and for a refined redshift experiment proposes to use the same spacecraft and ground equipment. Thus, in practice, it could be possible to do both investigations sequentially on the same space mission. Alternatively, these investigations could be done on separate missions. Similarly, equipment for accurate Doppler tracking of

interplanetary spacecraft is the experimental technique for some of the experiments in this booklet and for searches for gravitational waves. Again, multiple-objective missions are quite possible.

Finally, the experiments in this booklet may be classified according to the aspect of gravitational theory they investigate (see Table 2). The first three concern the Equivalence Principle, in its various forms. The Equivalence Principle is an initial premise upon which Einstein's theory and other metric theories of gravitation are based. If some implication of the Equivalence Principle fails an experimental test at some level of accuracy, then the validity of all theories based on it must be seriously reexamined at corresponding accuracy levels.

The Orbital Cryogenic Eötvös Experiment carries to low Earth orbit a family of experiments designed to test the Weak Equivalence Principle, which asserts that the ratio of passive gravitational mass to inertial mass is the same for all bodies, independent of their composition. Ground-based experiments have verified this assertion to a practical accuracy limit around 10^{-11} to 10^{-12}. In the free-fall environment of Earth orbit, an accuracy of 10^{-17} to 10^{-18} may reasonably be expected.

The H-Maser Redshift Experiment and the Beta-Decay Clock Experiment test an implication of the Equivalence Principle. The Equivalence Principle implies that the relative frequency difference $\Delta f/f_2$ of two identical clocks is equal to $\Delta\phi/c^2$, where $\Delta\phi$ is the difference in gravitational potential between the two clocks and c is the velocity of light. In these experiments, one clock or oscillator remains on Earth while the other is carried on a spacecraft in an eccentric Earth or solar orbit. Relative to the oscillator on the ground, the frequency change in the spacecraft oscillator is observed as it goes in and out of the gravity potential of the Earth or Sun. Here the essential contribution of space technology is to transport one oscillator through significant potential differences.

The H-Maser Redshift Experiment, the Beta-Decay Clock Experiment, and other similar clock experiments differ in the physics of the oscillator involved.[1] In principle, the frequency of an oscillator can depend on any of the four fundamental forces or on some combination of them. The question can then be asked whether the Equivalence Principle applies with equal accuracy to oscillators driven by different fundamental forces. The frequency of a H-maser depends primarily on electromagnetic forces. A beta-decay clock depends on the weak interaction. These experiments thus explore a deep question in the relationship of the fundamental forces of nature.

Whereas the first two investigations discussed in this booklet would be carried on a spacecraft in Earth orbit, the remaining investigations would be carried to other places in the solar system. For most of these, the objectives are conveniently couched in terms of what is called the Parameterized Post-Newtonian (PPN) framework. This framework serves as a "supertheory" encompassing a large class of gravity theories as special cases. In it, the effect of gravity on a test body depends on the value of several PPN parameters. The meaning of each of these parameters is briefly summarized in Table 3.

Because each theory of gravity assigns specific values to these parameters, a measurement of their real value in solar system dynamics enables one to determine the correct theory of gravity. The most important parameters from the point of view of choosing between theories are β and γ. However, other important measurements are in progress. These include the determination or the placing of bounds on a time variation in the gravitational constant G, the difference between inertial and passive gravitational mass for the Sun (Nordtvedt effect), preferred frame effects, effects of nonmetric gravitation, and effects from

TABLE 2. Space Gravitation Experiments

Previous Space Experiments	Aspect of Gravitation Tested	Results	Remarks
Viking and predecessors [2]	Gravitational time delay	Spatial curvature ($\gamma = 1 \pm .002$)	1976
Lunar laser ranging [3,4]	Equivalence Principle for gravitational interaction energy	No violation to 3 percent	1969-1975
Gravity Probe A [5]	Equivalence Principle	Frequency shift due to gravitational field correct to 1 part in 10^4	1976
Proposed Experiments		**Measurement Accuracy Goal**	
Orbital Cryogenic Eötvös Experiment	Weak Equivalence Principle	Difference in inertial and passive gravitational mass to 1 part in 10^{17}	More accurate than ground-based versions
Hydrogen Maser Redshift	Equivalence Principle	Frequency shift due to gravitational field to 1 part in 10^6	Refinement of Gravity Probe A
Beta-Decay Clock Experiment	Strong Equivalence Principle for weak interactions	Changes in decay rates due to gravitational field to 1 part in 10^7	Tests new aspect of the Equivalence Principle
Venus Orbiter Imaging Radar	Lorentz invariance of gravitational interaction	Preferred frame parameters α_1 and α_2 to 1 part in 10^3	More accurate measure of α's
Mercury Orbiter	Spatial curvature (γ)	γ to 5 parts in 10^4	More accurate measure of γ
Solar Probe	(Solar quadrupole moment, J_2)	J_2 to 2 parts in 10^8	J_2 affects other relativity measurements
Solar Coronal Sounder	(Properties of solar corona gravitational time delay)	Phase delay to 1 m	Corona corrections to time delay measurements
Relativity Gyroscope Experiment	Dragging of inertial frames	Drift rates to 1 marc sec/yr	See separate booklet
Gravitational Radiation Search	Existence of low-frequency gravitational waves	Strains to 1 part in 10^{16}	See separate booklet

a cosmic background of gravitational radiation.

TABLE 3. PPN Parameters

Parameter	What It Measures
γ	How much is space curved by mass?
β	How much nonlinearity is there in the superposition of two gravitational fields?
$\alpha_1, \alpha_2, \alpha_3$	Does the universe have a preferred rest frame?
$\zeta_1, \zeta_2, \zeta_3, \zeta_4$	Is total momentum conserved?
ζ_w	Are there galaxy-induced anisotropic effects?
δ	What is the post-Post-Newtonian (nonlinear) correction to γ?
$\dot{G}/G$	How fast is the gravitational "constant" changing?

For each investigation involving a mission to another planet or the Sun, the expected PPN parameter refinements are listed in Table 2. The subsequent sections for specific missions describe in more detail how these refinements would result from that mission.

It should be emphasized, however, that refinement of parameters is not an end in itself, but is only a simplified way to compare and categorize a set of measurements probing the very foundations of physical sciences. The real objective is an understanding of fundamental gravitational processes. Many of the most interesting astrophysical objects being studied today, such as pulsars, quasars, compact X-ray sources, and the universe itself, involve relativistic gravity in a most essential way. Often, the answers to what these objects are or how they behave depend sensitively on which theory of gravity is correct. For example, if Einstein's General Theory of Relativity is correct, then the gravitational source in Cygnus X-1 cannot be a neutron star. It is too massive. It can be only a black hole. But, if another theory is correct (Ni's theory, for example), then neutron stars may be arbitrarily massive, and our most compelling evidence for the existence of black holes disappears. For these and other reasons, it is important to perform gravitational experiments and to determine which gravitational theory predicts correctly the experimental results.

Experiment Characteristics

To date, the candidate experiments discussed herein have been examined in greater scientific detail than they have been studied in engineering terms. In general, they are experiment or mission concepts for which the next appropriate step would be a preliminary design study.

Table 1 gives some experiment characteristics that can be suggested at this time.

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ORBITAL CRYOGENIC EÖTVÖS EXPERIMENT

SCIENCE

Rationale

The Equivalence Principle is the foundation of Einstein's General Relativity Theory and of all other metric theories of gravitation that have been conceived since Einstein published his theory. It is possible that breakdown of the principle will occur at some level of increasing measuring precision. The history of science demonstrates that all theories have some limit to their applicability. Discovery of any violation of the Equivalence Principle would cause a revolution in our concepts and theories of physics and the universe.

The Equivalence Principle states that the ratio of passive gravitational mass to inertial mass is the same for all bodies independent of their composition. (This statement is often called the "Weak Equivalence Principle.") As a consequence, test bodies of different composition experience the same acceleration in a given gravity field. Modern experiments designed to test this principle can be thought of as highly refined versions of the famous experiment, popularly attributed to Galileo, which investigated whether balls of different materials, dropped from the Leaning Tower of Pisa, fell with the same acceleration. A simple test can be performed by measuring the period of a pendulum which is proportional to $\sqrt{M/m}$, where M/m is the ratio of gravitational and inertial mass. Around the turn of the century, R. V. Eötvös performed experiments with a torsion balance to measure the ratio M/m. In his experiments, the driving force was the centrifugal acceleration (due to Earth rotation) on the surface of the Earth. Experiments measuring the ratio M/m are commonly called Eötvös experiments.

The most recent tests of the Equivalence Principle have been performed by Roll[1] and Braginsky[2] and their coworkers. The reported accuracies are 1×10^{-11} and 2×10^{-12}, respectively. These experiments also used a torsion balance on the Earth. However, the driving force involved was the acceleration toward the Sun, which shows a 24-hour modulation period caused by Earth rotation. Ground-based Eötvös experiments have reached a practical limit around the 10^{-11} to 10^{-12} accuracy level because of disturbances induced by the environment on Earth (e.g., seismic noise).

Objective

The objective of the proposed mission is a test of the Equivalence Principle to the highest level of accuracy permitted by technology. Analysis has indicated that the proposed Orbital Cryogenic Eötvös Experiment could reach an accuracy of 10^{-17} to 10^{-18}, which is an improvement of 5 to 6 orders of magnitude over the best existing measurements.[3]

INSTRUMENT AND MEASUREMENTS

The quantity to be measured is the Eötvös ratio η given by

$$\eta = 2 \frac{(M/m)_A - (M/m)_B}{(M/m)_A + (M/m)_B}$$

M/m is the ratio of passive gravitational mass and inertial mass for two test bodies A and B. The two test masses consist of a hollow cylinder (about 20 × 20 cm) and a solid cylinder (about 10 × 10 cm) made of different materials and arranged in a coaxial configuration. Each cylinder is supported in a superconducting bearing with freedom of motion (over a limited distance) along the axes of the cylinders.

The two test bodies are in free fall in orbit around the Earth. A difference in the M/m ratio of the two cylinders would cause a differential acceleration of the two test masses; i.e., there would be a slightly different orbit for each cylinder. This would show up as a relative displacement between

the cylinders along their axes. With the satellite stabilized in an inertial mode, the acceleration on the test masses changes direction during orbital motion, which would result in a periodic relative displacement of the two cylinders with a period equal to the orbital period, as indicated in Figure 1. The experiment measures the relative displacement between the two cylinders.

The instrument is essentially a very sensitive differential accelerometer. The two coaxial cylinders are constrained by a superconducting bearing. Figure 2 illustrates the principle of the bearing.

The position detector operates in a feedback mode, measuring the force necessary to keep the two cylinders centered along the cylinder axes. The position detector is a superconducting quantum device (SQUID) magnetometer employing the principle of the Josephson junction effect. The experiment is enclosed in a liquid helium dewar which provides an operating temperature around 2 K. Superconducting shields will eliminate the influence of the ambient magnetic field.

The advantages of this orbital Eötvös experiment, which will yield a much more sensitive measurement as compared with past ground-based experiments are: increased driving force (about a factor of 1000), co-centered test masses, reduced disturbances (e.g., seismic), and cryogenic technology (magnetic shielding, extremely stable and sensitive position detectors).

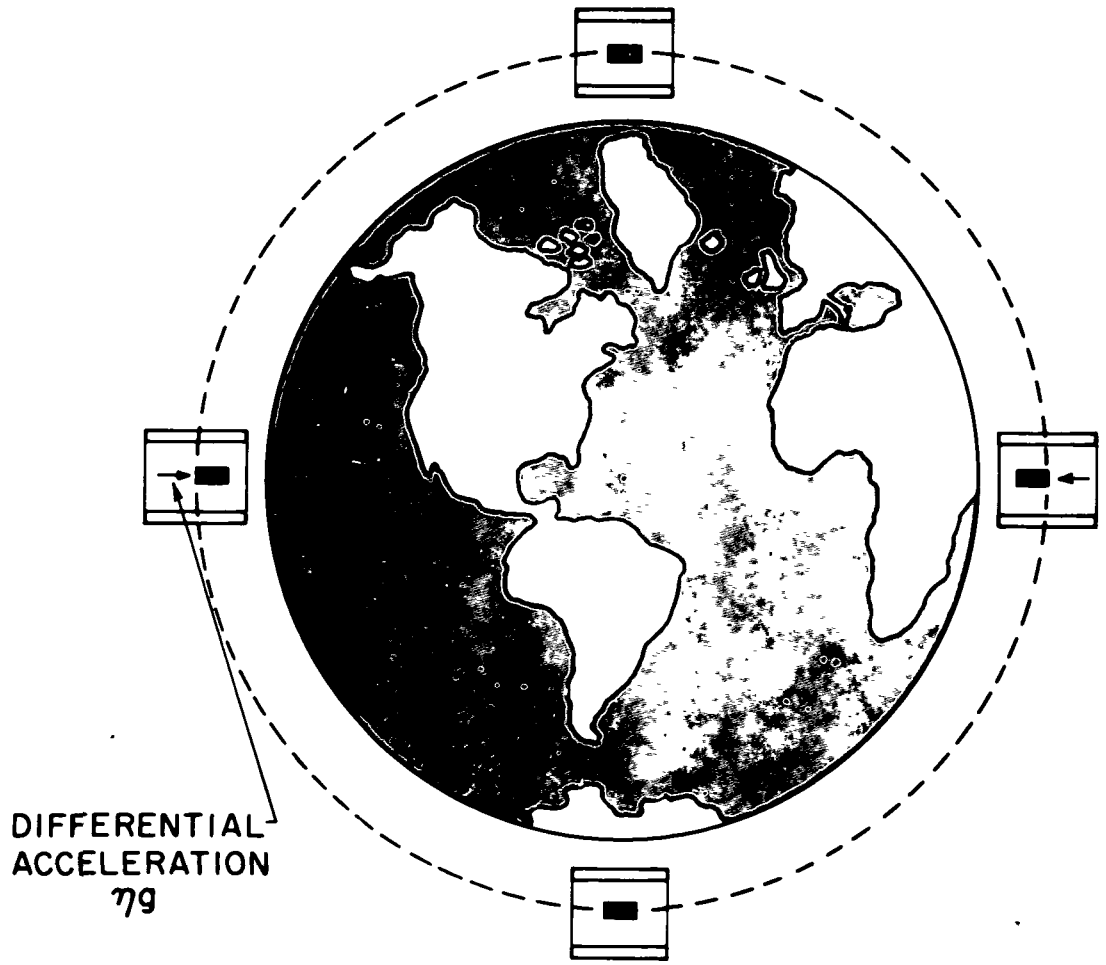

Figure 1. Experiment Concept.

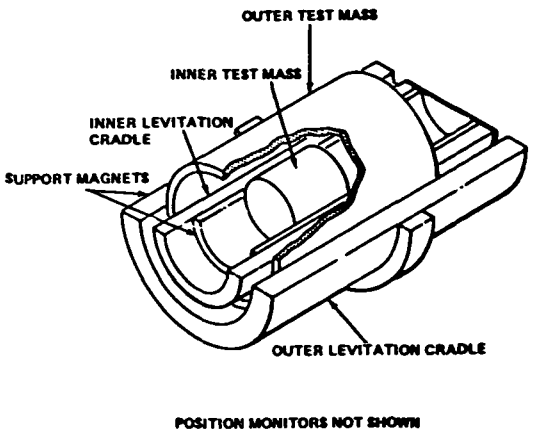

Figure 2. Equivalence Principle Accelerometer.

MISSION DESCRIPTION

The payload, a free-flying satellite, will be placed into a 400 to 600-km circular orbit by the Space Transportation System. The operational lifetime of the experiment is 3 to 6 months. The relative displacement of the test masses will be measured continuously during the mission. Data will be accumulated and stored on board for transmission to the ground at appropriate intervals. Data reduction and analysis will be performed during and after the flight.

Spacecraft Characteristics

The spacecraft consists essentially of a liquid helium dewar (see Figure 3). The spacecraft will be attitude stabilized relative to inertial space. A drag-free control system will reduce residual acceleration to a level of 10^{-12} g.

Spacecraft requirements could be met by the Gravitational Probe B (GP-B) spacecraft. The Eötvös experiment package could be substituted for the GP-B experiment package after retrieval of the GP-B satellite if this satellite is retrieved.

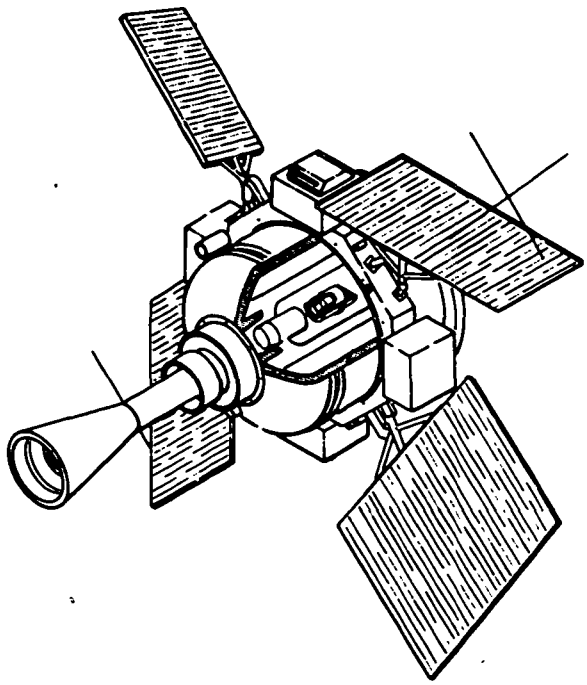

Figure 3. Spacecraft for Orbital Cryogenic Eötvös Experiment.

Options

An experiment of intermediate accuracy (10^{-14} to 10^{-15}) may be possible during a Spacelab mission. The accuracy-limiting factors are spacecraft acceleration and vibration noise. A Spacelab Eötvös experiment is presently under study. The ultimate experiment requires a free-flying satellite.

PROGRAM ASSESSMENT

The technology and principle of the superconducting bearing and the position detector have been developed and demonstrated in the laboratory at Stanford University. A ground-based experiment version is being developed at Stanford University. The present design of the superconducting bearing and position readout system is for a ground-based operation of the experiment. Modification of this design is needed for a space flight experiment.

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HYDROGEN MASER REDSHIFT EXPERIMENT

SCIENCE

Rationale

The proposed mission will perform improved measurements of the gravitational redshift, a phenomenon previously measured to lower accuracy.

According to Einstein's Equivalence Principle, the frequency of an oscillator or clock depends on the gravity potential. The frequency difference Δf of two identical clocks is given by

$$\frac{\Delta f}{f} = \frac{\Delta \phi}{c^2}$$

where $\Delta \phi$ is the difference in gravity potential between the two oscillators and c is the speed of light. The measurement of gravitational redshift represents a test of the Strong Equivalence Principle. The spacecraft will carry a hydrogen maser clock, and a similar clock will be in the ground station. While the spacecraft is in Earth orbit, the frequency of the two clocks will be compared by microwave signals. Because of the highly eccentric orbit, the spacecraft clock will experience a periodically varying gravitational potential that modulates the gravitational redshift.

Objective

A similar short-duration (2 hours) experiment was performed in 1976 with a suborbital rocket probe (Gravitational Probe A).[1] The accuracy of this experiment was 10^{-4}. The mission discussed here will use an advanced hydrogen maser clock with improved stability, and the measurement will be repeated many times during the Earth orbital phase.[2] The anticipated accuracy in the redshift measurement is 5×10^{-6}. At this level of accuracy, the experiment will break new ground, testing the internal self-consistency of the General Relativity Theory, the Special Relativity Theory, and the isotropy of light propagation.

The relative motion between spacecraft and ground station causes a large first-order Doppler effect as well as a second-order (relativistic) Doppler effect. The first-order Doppler effect can be eliminated automatically by proper processing of the signals of the four microwave links between spacecraft and ground station. The relativistic Doppler effect can be determined from the accurate measurement of the spacecraft velocity relative to the ground station.

INSTRUMENTATION

The instrumentation for this mission is based soundly on the experience with Gravitational Probe A (GP-A). Whereas GP-A had a three-link microwave system, this mission would add a fourth link to make the system completely symmetrical. An improved hydrogen maser would be employed, recognizing that substantial progress in technology has occurred since the early 1970's. However, the flight packaging concepts could be largely reused.

The four-link microwave system is completely phase coherent and symmetrical with respect to signal transmission (see Figure 4). The on-board equipment includes the hydrogen maser, transponder, antenna, and signal processing. The ground-station equipment is rather similar. The one-way and two-way Doppler measurements made in the spacecraft are telemetered back to the ground station. For redshift measurements, the first-order Doppler effect in the one-way transmission will be cancelled in real time by subtracting one-half the two-way Doppler phase from the one-way phase accumulation. The system operates at X-band with a single S-band auxiliary link that is phase coherent with one X-band link, to allow measurement of the columnar electron density in the ray path (for *a posteriori* ionospheric corrections).

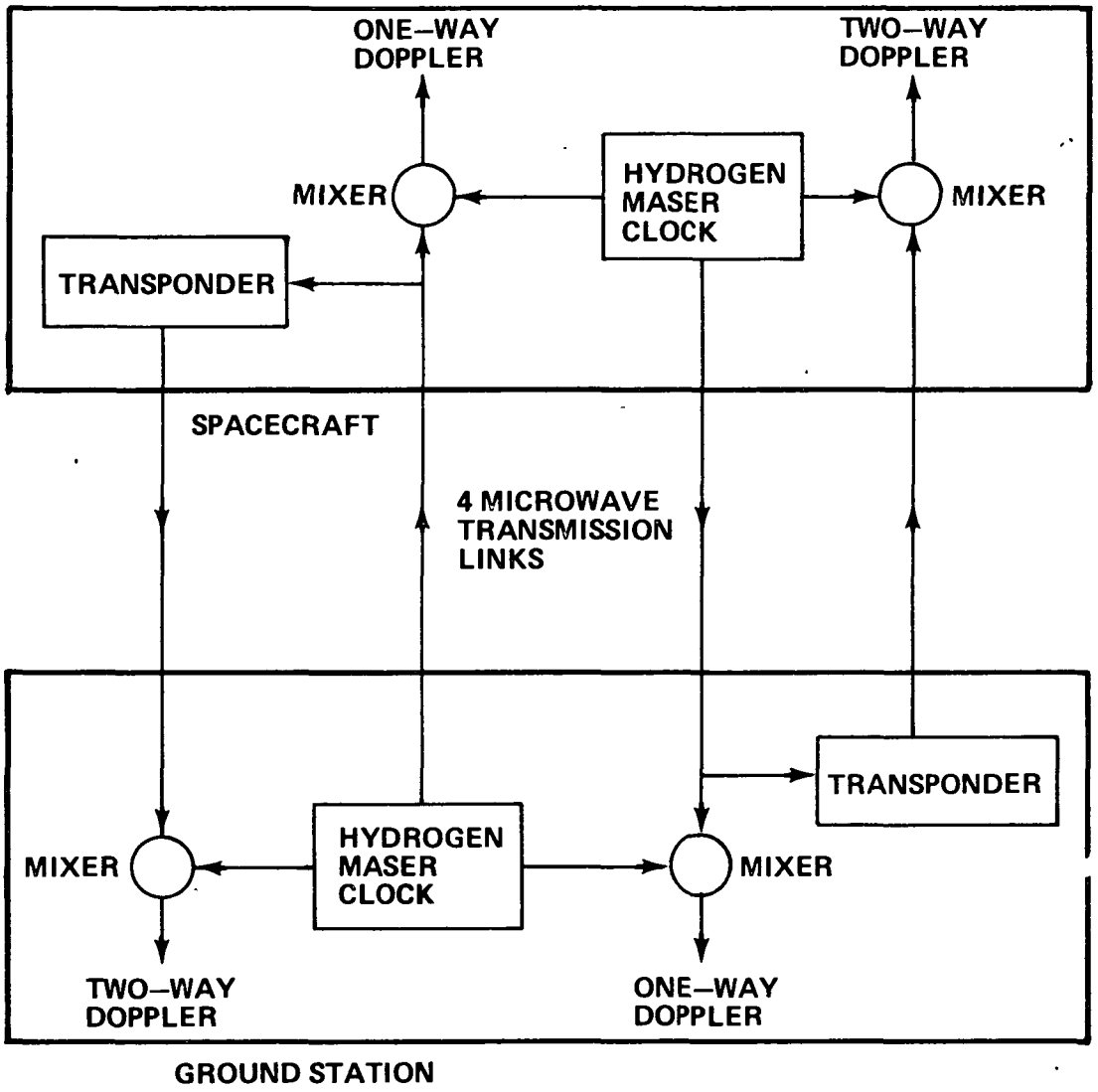

Figure 4. Four-Link Microwave System Concept.

HYDROGEN MASER REDSHIFT EXPERIMENT

MISSION DESCRIPTION

The spacecraft for this mission could be launched from the Space Shuttle. A separate propulsion stage is required for injection into synchronous Earth orbit. The criteria for selection of the Earth orbit are large eccentricity to obtain maximum variation of the gravity potential and continuous or nearly continuous visibility of the probe from the ground station. An eccentricity of 0.5 to 0.6 seems to be optimum when ground-station visibility and minimum elevation angle requirements are taken into consideration. The minimum mission will last an estimated 2 to 4 months. The redshift measurements could be made from a ground station with relatively small antenna size and low transmitter power located close to the equator.

Inasmuch as the instrumentation for this mission could be identical to that needed for a search for long wavelength gravitational radiation, the redshift measurements could be the first phase of a combined mission. The latter phase requires an interplanetary orbit (see separate booklet: Gravitational Radiation Searches and Gravity Wave Astronomy).

For an individual redshift mission, the spacecraft concepts used on GP-A would have to be modified somewhat to provide a several-month lifetime for the mission. For a combined mission, a spacecraft patterned after interplanetary spacecraft would be more appropriate.

PROGRAM ASSESSMENT

The technology required for this mission is basically available. The concept and systems evolved from the GP-A mission, which carried the first hydrogen maser clock into space. Further studies are required to define specific details of the mission.

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BETA-DECAY CLOCK EXPERIMENT

SCIENCE

Rationale

One of the basic assumptions of most current theories of gravity is the Equivalence Principle. In its strong form, this principle states that in a freely falling frame, the laws of physics take on their usual present form at all locations and for all times. It has been suggested that this principle may be violated if the gravitational constant G varies with time, and this is being investigated using celestial mechanics. Time variations in G were first suggested by Dirac in the 1930's. In the 1960's, a theory was advanced by Brans and Dicke which had time variations in G. This theory also had the property that G varied with position. Many other theories of gravity have this property,[1] and it can be summarized in the form

$$G = G_o[1 - 2(\beta + \gamma - \beta_2 - 1)U/c^2] \quad (1)$$

where β, γ, and β_2 are constants of order one which characterize the theory, U is the gravitational potential, c is the velocity of light, and G_o is the value of G when U = 0. In analogy with this, one might ask whether a similar variation might occur for the second weakest force in nature, namely the weak atomic forces responsible for the beta decay.[2] In analogy with Eq. (1), one might look for a variation in the weak interaction coupling constant G_w of the form

$$G_w = G_{wo}(1 + \alpha U/c^2) \quad (2)$$

where G_{wo} is the value of G_w when U = 0, and α is some constant on which we want to put upper limits by measurements of G_w at different gravitational potentials. If it is nonzero, this would be a violation of the Strong Equivalence Principle. This constitutes the rationale for doing an experiment to measure beta-decay rates or some related process at different points in a gravitational field. Any significant variation in G_w would have important astrophysical consequences.

There is no direct evidence that α is small. However, two arguments have been advanced to suggest that α must be less than 1. The first one is based on the fact that even though the part of the weak interaction responsible for beta decay is too small to influence Eötvös experiments at the present level of accuracy, these experiments still put significant constraints on α. In fact, by assuming conservation of energy, mass energy equivalence, and that the fraction of rest mass of matter contributed by the part of the weak interaction responsible for beta decay is approximately 10^{-11}, one can show that α must be less than 1. Another argument states that one must include in U the gravitational potential of the rest of the universe, and this is assumed to be of order c^2. This also implies that α is of order 1 or less. Both these arguments have assumptions that may not be valid. It is, therefore, believed that while an accuracy of order U/c^2 is a useful goal, an experiment of lesser accuracy may still be worth doing.

Objective

The scientific objective of the experiment is to search for variations in G_w with gravitational potential. The accuracy goal of the experiment is U/c^2, so that it is advantageous to obtain the maximum U available, i.e., solar orbit. This experiment will test a new aspect of the Equivalence Principle that has not been tested previously.

TYPICAL MEASUREMENTS REQUIRED

The type of experiment which could be done to measure variations in G_w would consist of measuring some process which is sensitive to G_w at different values of gravitational potential. Three different experimental techniques have been suggested:

(1) Direct counting of decay products from a radioactive source by electronic particle counters. Two versions of this approach have been proposed. One is to measure the alpha-decay products from a radioactive thorium source.[3] Since one alpha peak results from a decay following the beta decay, it is sensitive to a beta-decay rate; therefore, measuring the ratio of these particles to other alpha particles would reveal any variation in beta-decay rate and thus in G_w. Another experiment is to measure the X-rays following electron capture in a suitable source.[4] This is a weak interaction process and thus is sensitive to G_w. The resulting X-rays have a well-defined energy and are easy to count. Both these schemes have a basic accuracy limit due to counting statistics which is of order $1/\sqrt{N}$, where N is the total number of counts.

As an example of the time needed to reach the U/c^2 accuracy level in various orbits just from statistical fluctuations, consider the following example. For 10 detectors, each counting at 10^6 counts/sec (a feasible number), it would take 5 days at 4 solar radii, 30 days at 10 solar radii, and 5 years at 80 solar radii (Mercury's orbit) to reach the U/c^2 level. Thus, a close solar orbit is required for the schemes based on counting just from the statistical limitations. In addition, there are errors due to discriminator stability, dead-time stability, pulse pile-up, and detector-gain stability that need to be investigated.

(2) Direct measurement of detector output current. This would allow more active sources and thus overcome the statistical fluctuations. How accurately this type of measurement can be done is not known. Also, one could measure beta-decay current directly with no amplification.

(3) Chemical analysis. This method could analyze chemical composition of the products of radioactive decay after many half-lives. It is potentially very accurate, but no studies have been done to determine the attainable accuracy.

All these methods would require a highly eccentric orbit to sample different values of U. Also, a periodic modulation of G_w is easier to detect and separate from other instrumental drifts.

MISSION DESCRIPTION

The payload is launched into an eccentric solar orbit. The number of counts in specified periods is recorded and telemetered to a tracking station. The orbit is determined from the tracking data so that a record of gravitational potential versus time is available.

The scientific instrument might consist of one or more radioactive sources and detectors. The detectors could be gaseous, solid-state, or scintillation detectors. Each detector would have an amplifier and a high-speed counter that would count the number of pulses in given intervals of time (see Figure 5).

The alternative methods of doing the experiment, such as direct current measurement or chemical analysis, would require a similar type of orbit and similar spacecraft characteristics.

The payload is small. There is no particular constraint on the spacecraft other than some type of thermal control. This experiment could be done with other experiments on a deep space probe such as the close solar probe or other interplanetary missions.

PROGRAM ASSESSMENT

This experiment concept is in a preliminary stage of definition. Some experimental work has been done on the alpha counting method, but the ultimate achievable accuracy of this scheme is not known. Experimental studies of the other methods need to be done. Use of space technology to do the experiment is

essential inasmuch as the instrumentation must be carried through a large change in gravitational potential.

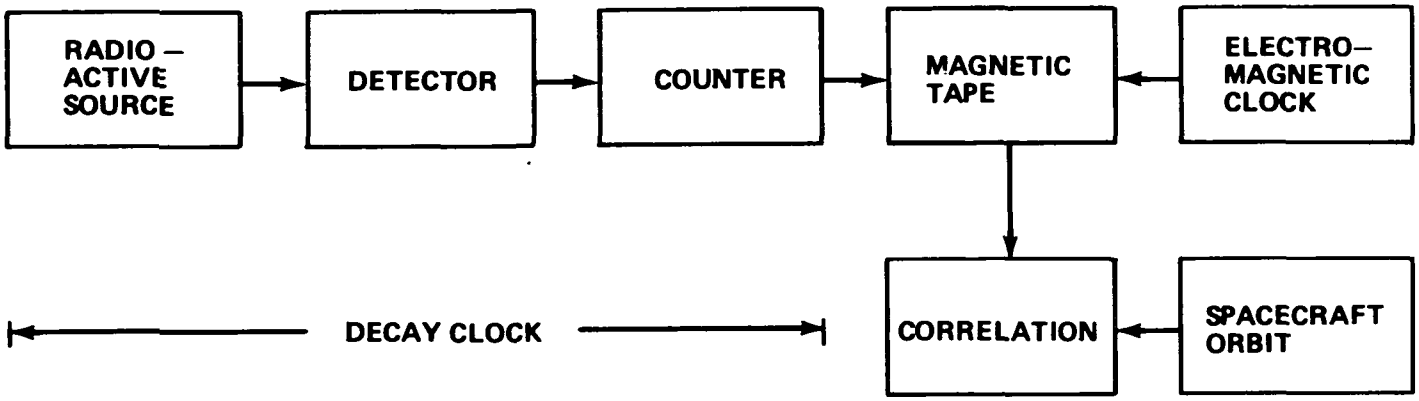

Figure 5. Experiment Concept.

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VENUS ORBITER IMAGING RADAR

SCIENCE RATIONALE

A number of important measurements could be carried out on missions to the inner solar system. One example of such a mission for which the relativity opportunities have been studied in considerable detail is the Venus Orbiter Imaging Radar (VOIR) mission. The primary objective of a VOIR Relativity Experiment would be to limit or determine preferred frame effects of gravitation that are zero in Einstein's theory. The parameter α_1, which at present is zero with an uncertainty of ± 0.1, could be determined with an uncertainty of ± 0.02 with 19 months of VOIR data or ± 0.001 with 2 years of data. The parameter α_2, which is known at present to ± 0.002 from Earth gravimeter measurements, could be improved to ± 0.0005 with 19 months of data and to ± 0.0002 with 2 years of data. Once α_1 has been determined from VOIR, it would be possible to use the lunar laser and other planetary ranging results to determine β to better than ± 0.009. At present, it is necessary to assume that theories of gravitation obey a full complement of conservation laws for energy, momentum, and angular momentum before a value and uncertainty can be assigned to β. With the addition of the VOIR results, this theoretical restriction would no longer be necessary, and we would have made significant progress toward a completely empirical description of the laws of gravitation.

MEASUREMENTS

The VOIR mission has many objectives. For purposes of illustration, the aspect of the mission of interest here is the accomplishment of accurate tracking and orbit determination while the spacecraft is in orbit around Venus. The determination of a circular orbit from a few revolutions of Doppler data is notoriously difficult. Fortunately, for the relativity investigation, only the orbital component along the Earth-Venus line of sight is required; and this component is determined almost directly by the Doppler data. A preliminary error analysis indicates that the Earth-Venus range can be determined to an accuracy on the order of ± 100 m or better. The limiting error is probably the gravity noise from Venus, not the instrumental error.

The preliminary error analysis was conducted for a VOIR near-circular orbit ($e \sim 10^{-3}$) at an altitude of 300 km above the surface of Venus. The configuration of Venus was near maximum elongation, and the near polar orbit was viewed almost face on. The inclination of the orbit to the plane of the sky was 22 degrees. Thus, the spacecraft was occulted by Venus only briefly as it dipped behind the equatorial limb of Venus to a depth of approximately 8 percent of the planet's radius.

The orbit determination simulation assumed that the Doppler data were accurate to ± 1 mm/sec at a sample interval of 60 sec. Gravity harmonics of the second and third degree were included in the orbit determination, and harmonics of the fourth and fifth degree were included as an unknown noise source. The uncertainties in all the harmonics were set equal to values given by the rule that the sizes of the nonhydrostatic normalized coefficients fall off in magnitude with the square of the degree. Experience with the Mariner 10 and Pioneer data for Venus indicates that the deviation of the gravitational field from sphericity amounts to no more than a few parts in 10^6 at the surface of the planet. This observation is consistent with the inverse square rule for the second-degree coefficients and makes reasonable an extrapolation to higher degree. The unknown nonhydrostatic component of the field dominates the orbit determination error along the line of sight. Additional studies are in progress to determine the extent to which this is the limiting error source. Preliminary analysis indicates that if continuous tracking data were available, the optimum strategy for the relativity experiment would be to produce an independent measure of Earth-Venus range every 12 orbital revolutions.

Relativity Error Analysis

An error analysis was conducted to determine the expected error in the PPN parameters (β, γ, α_1, α_2, ζ) as a function of mission duration. It was assumed that range data to Venus were available to an accuracy of ±100 m at a sample interval of 3 days from the tracking of the VOIR orbiter. In addition to the PPN parameters, the error analysis included six orbital elements for Venus, six orbital elements for Earth, and the astronomical unit. For the error analysis, it was decided that no theoretical constraints would be imposed except for those that are implicit to the PPN formulation of post-Newtonian gravity. Thus, within this formulation, the *a priori* errors introduced into the covariance analysis were all strictly empirical and were a direct consequence of current experiment.

The results of the covariance analysis were very important to the definition of a relativity experiment on the VOIR mission. Significant improvements in the preferred frame parameters α_1 and α_2 were indicated for mission durations approaching one synodic period (584 days) of Venus. Ranging to Venus was assumed to start on July 1, 1985, approximately 6 months before superior conjunction; and, by the time of inferior conjunction on November 5, 1986, both α_1 and α_2 had been improved by a factor of five, while tracking for a full synodic period resulted in order-of-magnitude improvements for both parameters. Data around superior conjunction (±5 degrees) were deleted from the error analysis because it would be very difficult to determine the Venus-centered orbit of VOIR from the noisy Doppler data in this region.

The other three PPN parameters (β, γ, ζ) were not improved significantly by the assumed VOIR tracking. However, an independent determination of α_1 and α_2 by VOIR not only yields important constraints on theories of gravity but also leaves other experiments free to determine β without ambiguity. The parameter γ is determined directly by ray-bending and time delay measurements at superior conjunction, and so VOIR is not a particularly attractive mission for this purpose. The remaining PPN parameter, ζ is best determined by Earth tide data. Thus, the primary scientific objective of a relativity mission on VOIR should be the determination of α_1 and α_2. Tracking of VOIR for 23 months could provide a measurement of α_1 to ±0.001, which is comparable to expected accuracies in the other PPN parameters in the 1985-1990 time period. However, no experiment other than VOIR has been identified to determine α_1 to this level of accuracy.

SCIENCE RATIONALE

Range and Doppler data from a Mercury Orbiter will be used to determine the orbit of Mercury over a period of at least 1 year. The technique consists of determining the motion of the center of mass of Mercury by tracking the Orbiter.

To gain an idea of the relative merit of a Mercury Orbiter in relation to other gravitational experiments, a preliminary error analysis has been performed which, although quite conservative and not complete, is nevertheless very illuminating.

The approximate covariance analysis of the Mercury Orbiter problem has been performed under the following assumptions:

(1) One measurement (normal point) to the center of mass of Mercury is available each day with a standard deviation of 10 m on each point.

(2) Normal points are available on a daily basis over a time period of 2 years.

(3) By means of dual-frequency tracking, both in range and Doppler, error contributions to the normal points from signal propagation effects in the solar corona are negligible.

(4) Data are excluded from the covariance analysis when Mercury is less than 5 degrees from the center of the Sun. This assumption is intended to account for possible difficulties with Doppler tracking of the Orbiter when Mercury is near the Sun at superior conjunction. No points are excluded.

(5) The parameters included in the covariance analysis are the six orbital elements of the Earth (assumed known initially to one part in 10^6), six orbital elements for Mercury (also assumed known initially to one part in 10^6), the relativity parameters (β, γ), the solar quadrupole (J_2), and the astronomical unit AU (assumed known initially to 1 km).

A number of 16×16 covariance matrices were computed for various assumptions on the initial errors in β, γ, and J_2. The results are given in Table 4.

The basic conclusion of this approximate error analysis on the Mercury Orbiter is that the chief benefit of this type of mission to experimental gravitation is in the very precise determination of the parameter γ. It is not possible to improve the parameter β very much beyond what can be achieved at present with lunar laser ranging data, and it appears that several more years of lunar laser data will improve the

TABLE 4. Preliminary Error Analysis on the Mercury Orbiter

β		γ		J_2	
Initial Error	Final Error	Initial Error	Final Error	Initial Error	Final Error
4×10^{-2}	3×10^{-3}	2×10^{-2}	5.8×10^{-4}	5×10^{-5}	3.7×10^{-7}
10^{-3}	0.95×10^{-3}	10^{-4}	0.99×10^{-4}	5×10^{-5}	1.2×10^{-7}
4.5×10^{-3}	1.1×10^{-3}	10^{-2}	5.6×10^{-4}	10^{-8}	10^{-8}

accuracy of β to the point where the Mercury Orbiter mission will not provide very much additional information. With respect to the quadrupole moment, the Mercury Orbiter would provide some good results.

The present conclusions are very strongly dependent on assumptions (1) through (5) of the Mercury Orbiter error analysis. These assumptions are consistent with the radio science experience on Mariner 9 and the Viking Orbiters at Mars, but it is quite possible that a Mercury Orbiter mission, dedicated solely to general relativity and J_2 of the Sun, could be designed to yield better results with less tracking time. Also, future improvements in the Deep Space Network radiometric system will influence the expected results dramatically. Much more work is needed on studies and analysis of experimental gravitation on Mercury Orbiter before the real potential of this mission is understood.

MEASUREMENTS

The determination of the orbit of the spacecraft with respect to the center of mass of Mercury is crucial, but a preliminary assessment of this determination indicates that the distance from the center of mass of Earth to the center of mass of Mercury can be achieved to an accuracy of ± 10 m with existing radio technology. Additional studies are needed to refine this result and to determine the impact of improvements in the Deep Space Network radiometric system on the determination of the Mercury orbit. Submeter accuracies are not out of the question.

The present difficulty with the Mercury orbit is that the best positional data are obtained by passive radar ranging from the surface. Mercury is not a particularly good radar target, and that, in combination with uncertainties contributed by planetary topography, limits the determination of the radar distance to Mercury to an accuracy of approximately ± 2 km. Improvement of two or three orders of magnitude is feasible with an Orbiter; and, consequently, gravitational experiments can be performed to much higher precision than at present.

SOLAR PROBE

SCIENCE RATIONALE

The Solar Probe mission uses Jupiter gravity assist to achieve an orbit with a perihelion distance of approximately 4 solar radii. The probe spacecraft will be tracked with the Deep Space Network.

The primary scientific data from a solar probe will be collected inside of 15 solar radii, over a time interval of approximately 33 hours. The gravitational quadrupole moment J_2 of the Sun will be obtained to an accuracy of $\pm 2 \times 10^{-8}$ with Doppler tracking. Current solar interior models predict a value of J_2 between 8.3×10^{-8} and 1.4×10^{-7}.

The tests of general relativity can be performed to better than 0.5 percent accuracy with Doppler tracking near the Sun. Improvements would result from the incorporation of an on-board hydrogen maser. Further studies are needed to define the expected accuracy of scientific measurements from the hydrogen maser.

MEASUREMENTS

Perhaps the most difficult technological problem is associated with the telecommunication system. Because of the high electronic interference near the Sun, the radio system will have a much lower signal-to-noise ratio than is typical of other space missions; and, hence, with the standard NASA transponder, the receivable bit rate will be lower ($\sim 10^3$ bit/sec). In addition, the Doppler accuracy will be degraded significantly near perihelion unless innovative radio techniques are used. A preliminary assessment of the problem suggests that an upgrading of the spacecraft transponder and the Deep Space Network radiometric system will be required so that X-band (3 cm) uplink and downlink can be used during two-way tracking near the Sun. This possibility needs further study and analysis, as do a number of other options, including the incorporation of a hydrogen maser frequency standard on board and a transmission from the spacecraft in the K-band.

MISSION DESCRIPTION

The spacecraft time of flight to Jupiter is approximately 1.5 years, and the flight time from Jupiter to Sun is approximately 2 years. The total mission duration of 3.5 years can be shortened by as much as 1 year for high launch energies. With low energies of 0.110 km^2/sec^2, the Space Transportation System can inject 850 kg. This is more than sufficient for a basic Solar Probe design.

The spacecraft bus is protected by a roof-type thermal shield for solar encounter. Made of MgO or MCO_3, this shield will keep the bus temperature below 60 C for the duration of the flyby; consequently, an extended mission is possible. A maneuver of 1.3 km/sec at perihelion could be used to provide annual close flybys of the Sun.

A drag-free control system must be included with an accuracy of 10^{-10} g in all three axes of translational freedom. It is estimated that approximately 30 kg of propellant will be needed over the duration of the standard mission. Considerable analysis and modeling work are needed before the drag-free system can be specified.

SOLAR CORONAL SOUNDER

SCIENCE RATIONALE

A spacecraft orbit is selected such that a space probe stays in or near superior conjunction at a heliocentric distance of approximately 1 AU. The position of the space probe on the sky can be made to swivel between a selectable elongation west and east of the Sun, and also north and south if desired, by selecting an orbit with the same period as the Earth but a slightly higher eccentricity or a slightly higher inclination if north-south excursions are desired.

Based on a computer covariance study, it has been established that a significant new test of the relativistic gravitational time delay is possible with the Solar Coronal Sounder. It was assumed that dual-frequency ranging was available in order to calibrate the phase delay produced by the corona to within ±1 m. The limiting error source then appeared to be nongravitational forces on the spacecraft. It was found that with a conservative estimate of 10^{-12} km/sec^2 for unmodeled nongravitational acceleration, an independent measurement of the time delay comparable to the Viking result was possible. Reduction of the nongravitational noise source below the 10^{-12} km/sec^2 level could provide the best determination of the time delay to date.

MISSION DESCRIPTION

The transfer orbit to the desired orbit is strictly heliocentric with a typical transfer time of 2.5 years. A terminal maneuver is executed near the superior conjunction location to achieve the final orbit for coronal sounding. The major objective of the mission would be the characterization of coronal plasma densities by microwave techniques, but a test of general relativity would be an additional result.